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AN INTRODUCTION TO THE ASSURANCE OF HUMAN PERFORMANCE IN SPACE SYSTEMS

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An Introduction to the Assurance of Human Performance in Space Systems

Written under contract at the Baltimore Division of the Martin Marietta Corporation for the Reliability and Quality Assurance Office NASA Headquarters

Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1968
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Foreword

The role that man plays as a functioning element and as a potential source of error in space technology is widely recognized in a general way. NASA Reliability Publication NPC 250-1, entitled "Reliability Program Provisions for Space System Contractors," gives attention to this problem in calling for an intensive effort to eliminate potential sources of human-induced failure throughout a project's life.

In practice, there is a tendency either to implement a solution for this problem fully, with a formal program of human factors activities conducted by specialists, or to give it inadequate attention. Larger programs, particularly those in which the hardware is man-operated or man-rated, fall in the former class, and other programs frequently fall in the latter.

Since all NASA systems, both manned and unmanned, must be fabricated, handled, tested, and operated, it is important that the design-development effort of any project, small or large, give an appropriate degree of attention to preventing human-induced failures, particularly in these areas; in effect, the effort must help in assuring human performance. The present publication is intended to provide some guidance in determining what human-performance assurance effort is appropriate for various projects and to show how this effort relates to the various phases in the development cycle. The approach used provides a brief and concise description of:

(1) The content and order of overall programs of human factors activities fitting the life cycle of different projects
(2) The degree of pursuit appropriate for each of these elements of activity in the various kinds of projects

Intensive coverage of each of the individual activities is beyond the scope of this document. For further pursuit in these areas, the text refers the reader to appropriate sources in the literature.

This publication was prepared for NASA Headquarters by the Martin Marietta Corp. under contract NASw-1128. The principal author is L. J. Lewandowski of the Baltimore Division of the Martin Marietta Corp., and the effort has been guided and edited by D. S. Liberman of this office. However, NASA field installations and Headquarters offices have provided significant assistance by constructively reviewing and commenting on the drafts; this assistance is gratefully acknowledged.

This document is directed toward reliability assurance personnel and project personnel and not toward human factors specialists. The information provided is generic and descriptive and is not intended to be mandatory.

John E. Condon, Director
Reliability and Quality Assurance
Office of Industry Affairs
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Contents

CHAPTER 1

Introduction

Since the advent of the "Space Age" (approximately October 1957), an increasing concern has grown over the problem of human error and its effects on space-program development. One of the driving forces in human-induced-failure investigations has been the increasing number of reported malfunctions directly traceable to human performance or lack of performance. Several studies (refs. 1, 2, and 3) have mentioned human-induced failures as the cause of as much as 40 to 50 percent of all system discrepancies. Associated costs have been estimated in the millions without even including those of related problems such as increased hazard potential to man and machine.

In order to offset these mounting costs, increased emphasis is being placed on measures to reduce and eliminate human-induced failures. In the area of assessment and analysis, attempts have been made to quantify human performance in the accomplishment of various system functions (ref. 4), but scarcity of data has severely limited progress in this area. However, considerable progress has been made in developing methods and techniques for detecting and eliminating potential human-error sources in the areas of design features, procedures, and various types of work situations.

The present document deals with the latter approach. The purpose of this document is to present general guidelines and techniques applicable to space programs for reducing or eliminating sources of human-induced failures.[1] These guides are provided in support of NASA Reliability Publication NPC 250-1 (ref. 5), which specifies reliability program provisions for contractors. The paragraphs of reference 5 which relate to the prevention of human error are given in appendix A of the present paper.

The approach used herein is:

(1) To introduce the reader to these techniques within an overall framework of human engineering and serviceability functions, and to discuss them generally as they apply to projects of differing size and significance at each of the major phases of the project's evolutionary cycle. This is done in chapter 2.

(2) To present an example in which the techniques are applied to a specific project. The system selected is a hypothetical Micrometeoroid Deep Space Satellite (MDSS), a concept representing an unmanned satellite project in the medium-to-small class in cost, complexity, and significance. Chapter 3 fully describes this MDSS example.

A list of terms used in this publication and their definitions is given in appendix B.

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[1]Although potentially useful for any space program, the information provided here is expected to be most useful to smaller projects which do not employ full-time human factors specialists.

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CHAPTER 2

Human Engineering and Serviceability in System Development

This chapter provides a general overview of human engineering applications and serviceability for space programs of varying complexity, cost, and national significance.

The first step in determining what kind of effort is appropriate for assuring effective man-machine interaction in any space program lies in examining the nature of the program itself. Each project has its own peculiar characteristics and requirements. The effort required for it will, therefore, depend on such interrelated program variables as:

(1) Cost
(2) Complexity
(3) Experience with similar systems
(4) Degree of national significance

Little formal human engineering and serviceability activity, for example, would be required in developing an unmanned system to be built and used by highly experienced, knowledgeable personnel familiar with both equipment and procedural tasks. At the other extreme, an extensive program would be initiated for situations where machines must be "human-proofed" (designed so that personnel with minimum training and experience can operate and maintain them) or "man-rated" (designed to meet specific standards of performance and reliability for manned flight missions). The majority of space programs, however, do not conform to either of these extremes but fall in a broad intermediate category requiring varying degrees of human engineering effort. In order to assist in defining the nature and extent of this effort, this chapter first develops:

(1) A method for classifying programs and systems according to mission complexity and significance
(2) A list of human engineering and serviceability functions appropriate for specific development phases of the programs so categorized

With regard to the first item, space programs and systems may be classified according to the eight separate categories of table I. An inspection of these categories reveals that one or more of them may be applicable for any given space program. A program such as the Apollo, for example, would be classified in categories A, D, and G. The reader must determine the number and kind of categories that most suitably represent his particular program and its systems.

After a basis for categorizing space programs as given in table I has been established, levels of effort for human engineering and serviceability functions appropriate for implementation during each of the successive project phases for each of the various program categories may be identified and recommended as in table II. An unmanned spacecraft of average-to-low cost and complexity,

[2]A program of "high national significance," for instance, may be defined as one based on the highest standards and most rigid requirements for mission success. (Examples: A manned spacecraft, a man-rated launch vehicle, or a major space probe of the Surveyor class.)

Table I.—Space Project Hardware Categories

Category	Description
A	Manned spacecraft
B	Unmanned spacecraft which is highly complex and costly or of high national significance
C	Unmanned spacecraft of average or low complexity, cost, or national significance
D	Man-rated launch vehicle
E	Launch vehicle for category B spacecraft
F	Launch vehicle for category C spacecraft
G	Operational ground equipment (OGE) for category A or B spacecraft on category D or E vehicles
H	OGE for category C spacecraft on category F vehicles

for instance, falls within the C category. It is then seen from table II that the appropriate human engineering functions for full attention[3] on this project are:

(1) Prepare serviceability and maintainability analyses
(2) Assist in development of operational and maintenance procedures
(3) Review procedures and observe operational tests

For this same spacecraft, lesser attention is advised in performing the following functions:

(1) Review the system requirements, analyze the mission, and allocate functions by man-machine function analysis
(2) Assist in predesign and design trade-offs
(3) Participate in mockup activities
(4) Participate in design reviews
(5) Investigate and analyze human error sources during fabrication
(6) Observe preparations for flight test and test support activities

Finally, the table recommends that the activities not included in the two preceding lists be considered as requiring only minimal effort for this class of project.

Information from tables I and II can be applied to other projects in a similar manner. (See chapter 3 for a detailed example of how these tables are implemented during the design and development of a hypothetical, unmanned satellite in the average-to-low complexity class (the MDSS).

If it is assumed that the appropriate human engineering program has been defined for a particular system or project, a question arises as to the amount and kind of manpower required for implementing it. Manned systems, such as the Apollo, have employed from 40 to 50 human factors engineers and life scientists during certain phases of design and development. Smaller

[3]Since this program will probably not have human engineering specialists, these functions should be performed by a member of the project team assigned to cover the human engineering area.

Table II.—Human Engineering and Serviceability Functions During System Development

Activity	Degree of participation required for space hardware category —							
	A	B	C	D	E	F	G	H
Engineering design phase								
Predesign and early design activities								
Review system requirements and analyze mission (pp 6, 18 & 19)	●	●	⊕	●*	●*	⊕*	●	●
Allocate functions by man-machine function analysis (pp 6, 7 & 19 to 22)	●	●	⊕	●*	⊕*	⊕*	●	⊕
Prepare operator task analyses[c] (pp 8, 22 & 23)	●	○	○	●*	⊕*	⊕*	●	⊕
Human engineering of displays, controls, work-space layouts, etc.[c] (pp 8 & 22)	●	○	○	●*	⊕*	○*	●	⊕
Prepare serviceability and maintainability analyses[c] (pp 8, 9 & 24 to 27)	●	●	●	●	●	●	●	●
Assist in determining trade-offs involving human performance and serviceability; participate in preliminary design reviews[c] (pp 10 & 24)	●	●	⊕	●	●	⊕	●	⊕
Hardware development and operations phase								
Development and prototype test activities								
Monitor incorporation of human engineering and serviceability criteria (pp 10, 11 & 25 to 28)	●	●	⊕	●	●	⊕	●	⊕
Prepare personnel requirements data (p 11)	●	⊕	○	●	⊕	○	●	⊕
Assist in development of operational and maintenance procedures (pp 11 & 28 to 31)	●	●	●	●	●	●	●	●
Participate in mockup and simulation activities (pp 12, 29 & 32)	●	⊕	⊕	●	⊕	⊕	●	⊕
Participate in prerelease design reviews (pp 12 & 32)	●	●	⊕	●	●	⊕	●	⊕
Fabrication and flight hardware test activities								
Investigate and analyze human error sources (pp 13 & 32)	●	●	⊕	●	●	⊕	●	⊕
Perform observational studies; make recommendations (pp 13 & 14)	●	●	○	●	●	○	⊕	⊕
Prelaunch and operational activities								
Review procedures and observe operational tests (pp 14 & 33)	●	●	●	●	●	●	●	●
Observe maintenance and support operations (pp 14 & 33)	●	●	⊕	●	●	⊕	●	⊕

Legend:
- ● Needs active formal participation of human engineering technologies.
- ⊕ Needs less attention to human engineering considerations (as a part of other engineering effort).
- ○ Factor for consideration, but only minimal formal effort is required.
- * Applies primarily to planning for checkout and countdown features.
- c This task continues or is refined later during development and prototype test activities.

unmanned satellite programs generally either do not require human factors specialists, or, at the maximum, require the services of consultants for only limited time periods. System and design engineers working on the latter programs must usually provide the proper attention to human factors.

The reader may estimate the amount and kind of human factors participation recommended for his program by reviewing its unique requirements in conjunction with the information in table II. The following paragraphs describe the human engineering functions listed in table II for each of the program phases.

PREDESIGN AND EARLY DESIGN ACTIVITIES

REVIEW SYSTEM REQUIREMENTS AND ANALYZE MISSION

The first task in planning the human engineering effort for any program is to analyze its general and functional requirements. A list of things to be done by (or to) the system and the constraints under which they must be accomplished will result. This review provides the basis for planning all subsequent human engineering functions.

The review of system requirements is followed by a mission analysis, which describes the mission with sufficient clarity to facilitate further the performance of human engineering analyses and efforts. Steps in this analysis are:

(1) Determination of the sequence of basic functions and events that the system will perform or encounter throughout its mission life.
(2) Separation of this sequence into segments as necessary to facilitate description.
(3) Preparation of flow charts and time-line analyses for each segment of the mission sequence.

The degree of formality and detail used in performance of human engineering mission analysis will vary with the complexity, criticality, cost, and significance of the system and mission. If the system in question involves the higher levels of these factors, each step in the foregoing sequence would be carried out in a fully formalized manner. On the other hand, systems characterized by lesser levels of these factors might well permit the development of plans for further human engineering activities almost directly from the description of the sequence of mission functions or might require only minimal formalization of the intermediate steps. (Reference 6 contains a description of these activities for project Apollo, while chapter 3 of the present publication describes the analogous activity for a hypothetical small unmanned satellite (the MDSS).)

FUNCTION (MAN-MACHINE) ANALYSES

The preceding review of system requirements serves as a guide in preparing the function analysis.[4] A function analysis identifies what the roles of man and machine, and their interaction, will be for meeting each of the requirements imposed on a system. The degree of detail involved in performing the analysis will depend on the space program category involved (see table II). An example of a function analysis format for a typical OGE function may be found on pages 20 and 21.

In order to assist in making any allocation of man-machine activities, several listings are available as guides for determining which functions or operations a man can do better than a

[4]The man-machine analysis made at this time is subject to further refinement and verification based on detailed human engineering task analysis and design trade-off activities which occur as later steps in the design process.

machine and those which a machine can perform better than man. These lists have been summarized in table III.

Table III.—Man-Machine Capabilities

Human superiority	Machine superiority
1. Originality (ability to arrive at new, different problem solutions)	1. Precise, repetitive operations
2. Reprogramming rapidly (as in acquiring new procedures)	2. Reacting with minimum lag (in microseconds, not milliseconds)
3. Recognizing certain types of impending failures quickly (by sensing changes in mechanical and acoustic vibrations)	3. Storing and recalling large amounts of data
4. Detecting signals (as radar scope returns) in high-noise environments	4. Being sensitive to stimuli (machines sense energy in bands beyond man's sensitivity spectrum)
5. Performing and operating though task-overloaded	5. Monitoring functions (even under stress conditions)
6. Providing a logical description of events (to amplify, clarify, negate other data)	6. Exerting large amounts of force
7. Reasoning inductively (in diagnosing a general condition from specific symptoms)	7. Reasoning deductively (in identifying a specific item as belonging to a larger class)
8. Handling unexpected occurrences (as in evaluating alternate risks and selecting the optimal alternate, or corrective action)	
9. Utilizing equipment beyond its limits as necessary (i.e., advantageously using equipment factors of safety)	

One of man's greatest limitations when functioning as a system component is his low information-handling rate, even when he is engaged in a single task (ref. 7). This limitation, in turn, is further degraded by man's limited buffer storage (immediate memory) capacity. On the plus side, however, are:

(1) Man's ability to handle a great variety of different information-processing tasks
(2) Man's capability to adapt to new tasks or environments and learn new skills
(3) Man's judgmental ability in devising newly required procedures or resolving unexpected contingencies

The primary objective, therefore, in man-machine analysis is not the determination of whether a man will do a better job than a machine but rather of whether he can do an adequate one for less money, less weight, and less power and with a smaller probability of failure and need for maintenance.

OPERATOR TASK ANALYSES

The function analysis previously discussed deals with the allocation of system functions to man or machine or a man-machine combination. The next human engineering activity to be performed requires a more detailed analysis of each manned or semiautomated function in order to arrive at human information and response requirements which will serve as design inputs. This type of analysis is broadly called a task analysis; it involves time-line analysis in most cases and is supplemented by link analyses in the most extreme cases (see appendix B for definitions). For highly complex manned systems or operations, such as manned spacecraft, it is essential to conduct these analyses in considerable detail in order to assess man-machine design requirements and to obtain necessary basic information for establishing personnel requirements and training requirements. However, task and time-line analyses in a generally less detailed form are also of value for smaller systems as an aid in establishing certain design requirements and in determining operator task loading and the time scheduling of portions of the operating sequences. The basic elements of task analyses are descriptions of:

(1) Operator inputs and outputs in system operation and maintenance
(2) Equipment inputs and outputs
(3) Skills and knowledges required in task performance
(4) Potential equipment malfunctions
(5) Characteristic human errors to watch for and prevent

A task analysis format used for analyzing operational ground equipment during the Gemini program is given as exhibit 1. An example of an analysis for an unmanned satellite activity is given in chapter 3 as exhibit 3.

HUMAN ENGINEERING OF DISPLAYS, CONTROLS, AND OTHER EQUIPMENT FEATURES

The foregoing task analyses provide basic data for attaining the primary goal of human engineering: to design equipment to simplify the requirements imposed on man. The equipment in the Gemini case includes both that used onboard spacecraft in their operation and control and that used in their operational test support and maintenance activities. It will involve such major components as displays, controls, panels, and chassis and their operational configuration or work-space arrangement.

The human engineering of equipment design is thoroughly described in a number of texts and manuals in this field (see refs. 8, 9, and 10). Both empirical studies and intuitive "common sense" experience have been used in deriving principles and specifying design requirements and criteria. Two of the most recent documents in this area especially addressed to design engineers working on space programs are references 11 and 12.

SERVICEABILITY AND MAINTAINABILITY ANALYSES

General Considerations

One of the most important tasks associated with the human engineering of spacecraft and associated operational ground equipment involves preparing serviceability and maintainability analyses. As a means of human error prevention, these analyses are concerned with manned activities in maintaining systems in an efficient and safe way (especially during prelaunch operations). They contribute to the development of equipment onboard orbital vehicles as well as to the design and/or selection of displays, controls, consoles, and facilities to test and maintain them.

Although important for any space project, serviceability analyses are especially required when the mission contains critical launch window constraints (as on the Gemini program, ref. 13)

Date 8/62 Subject Task Analysis-Malfunction Detection System (MDS) Test Set

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By [illegible]

Time	Task	Display/Control Description	Display Indication (Critical Value)	Operator		Response	Remarks (Including Potential Malfunction)
				Action	Decision		
Precountdown (Prior to T-300 min)	1. Turns on test set power	Transilluminated switch/indicator for AGE power	Light indicates on or off	Manually depresses switch	Assures AGE power is on	Light illuminates white	
Precountdown (Prior to T-300 min)	2. Verifies panel indicator lamps	Push-button switch	Status of all lamps	Manually depresses switch and checks panel lamps	Decides to replace lamps if necessary	All lamps illuminate	May fail to scan entire panel.
Precountdown (Prior to T-300 min)	3. Performs check of circuits for MDS sensors	Transilluminated switch/indicator for "Monitor Circuits." Indicators for: a. Launch status b. Thrust chamber pressure switches (Stages I & II) c. Overrate d. Spin motor rotation detector (SMRD) e. L/V shutdown f. Lockout timers g. Timer status h. Timer start voltage	Lights indicate normal or malfunction	Manually depresses "Monitor Circuits" switch and holds for check of indicator lights.	Initiates corrective action if lights indicate malfunction	All lights indicate green	Releases switch to off position after check. (This task is one of a series of self-verification tests for the MDS test set.)

Exhibit 1.—Example of a task analysis worksheet for Gemini operational ground equipment.

or susceptibility to single-point failures through human error in prelaunch operations. Serviceability analyses lead to basic hardware decisions involving:

(1) Location of test and service points
(2) Mounting and packaging of components
(3) Location of maintenance access panels
(4) Types of connectors and fasteners required
(5) Routing of lines and cables
(6) Any other design feature which will make it difficult to damage or destroy equipment

The foregoing items are considered with a number of others in a detailed description of a serviceability analysis for a typical unmanned satellite program. (See chapter 3.)

Safety Features

In the predesign/design phase, safety features pertaining to both personnel and equipment are also identified and specified through human engineering and serviceability analyses. These help to detect hazardous and potentially hazardous conditions in the planned operating and test environments. Safety provisions usually recommended include:

(1) Fail-safe features in critical launch control and airborne equipment
(2) Lock-out switches or guarding of controls which initiate hazardous operations (such as crane movement, engine ignition, etc.)
(3) Protection against premature squib ignition
(4) Crew safety devices including emergency escape equipment
(5) Equipment design features which minimize or remove electrical, mechanical, and toxic hazards to personnel
(6) Adequate illumination in both work and test areas
(7) Effective warning devices (visual and auditory)
(8) Adequate accessibility
(9) Noise control

(Safety feature examples are listed with the serviceability and maintainability tables in chapter 3.)

DESIGN TRADE-OFFS

An important, continuing function in the design phase is to assist those engineers concerned with making design trade-offs. These trade-offs will involve reviewing the requirements of human engineering, reliability, maintainability, logistics, and other functional specialty areas on preliminary equipment design.

In order to support trade-off decisions, information on manned functions and activities (from initial task and serviceability analyses) must be clearly and efficiently presented to responsible system and project engineers during early design.

Design features considered as having very slight effect in causing human errors may be allowed during the making of trade-off decisions. However, data and assumptions underlying all trade-offs must be documented in order to have this information available for subsequent design reviews. Some deficiencies may occur later which are directly traceable to human engineering design features initially recorded as "having only slight effect." It will then become necessary to reclassify these features as significant sources of potential system failure.

DEVELOPMENT AND PROTOTYPE TEST ACTIVITIES

The primary human engineering effort during development testing is to assure that adequate human performance and serviceability criteria have been met in equipment design. This is essentially a monitoring activity which includes continuous, timely review of drawings, test practices and procedures, manufacturing plans and procedures, and design changes with project personnel.

In addition to monitoring, the development test phase includes such human engineering functions as:

(1) Preparing personnel requirements information
(2) Assisting in developing procedures
(3) Participating in simulation and/or mockup activities

PERSONNEL REQUIREMENTS DATA

Personnel requirements data are descriptions of the number and kinds of personnel required to perform each of the significant tasks in the operation, maintenance, test, and handling of a space system. This information is usually generated during the development stage of the project. As with most other human engineering tasks, the degree of formality necessary in preparing personnel requirements data depends on the complexity of the system and significance of the program. These data serve as a basis for:

(1) Production of instructional materials and aids
(2) Development or procurement of training devices
(3) Preparation of test, operational, and maintenance procedures and plans

The last item, which is an integral part of all space programs regardless of complexity, is described more fully as follows.

DEVELOPMENT OF PROCEDURES

When the number and kind of personnel required for a particular space system have been estimated, the next step is to assist in developing appropriate procedures for equipment operation and care. Since inadequate procedures have been found to be a primary source of human error, it is highly important to provide clear descriptions of what the operator is to do in checking out, testing, operating, and maintaining airborne and operational ground equipment. The following items should be stressed in all procedures preparation:

(1) Information should be presented clearly and completely in a step-by-step format
(2) Supplementary tables, charts, figures, etc. should be included only to clarify procedural steps
(3) Superfluous or confusing items (verbiage, etc.) should be avoided
(4) Procedures should be revised concurrently with design or prototype test changes
(5) Provisions should be included for handling contingencies or discrepancies, including those with which an operator may be unfamiliar

(Exhibits 4 and 5 in chapter 3 are specific examples comparing desirable and undesirable features in test procedures.)

Item (5) calls attention to problems which an operator may meet outside his normal work operations. The other four items emphasize the need for thorough, clear, and effective instructional material to cover his normal, everyday activities in manufacturing and test areas. Documents such as manufacturing plans, safety procedures, work orders, and operating procedures are included. The supervision must foster a basic awareness and understanding of the need to follow these established practices as an important means of eliminating human-induced equipment failures.

SIMULATION ACTIVITIES

After preliminary equipment design inputs and contributions to procedure preparation, human engineering efforts for larger programs (as the Apollo or Gemini) usually become involved with mission or function simulators. For unmanned programs, the use of simulators as such is rare.

During the simulation period, one is concerned with identifying design characteristics, environmental factors, and operational contingencies which might adversely affect personnel. Test runs are performed under both routine and emergency conditions. Data collected from these runs are analyzed for actual and potential causes of equipment malfunctions due to human error. (A description of crew performance during simulated lunar missions may be found in ref. 14.)

A special case considered as a functional equivalent of simulator usage is that involving mission operations training activities. Typically, the mission operations area includes an intimate interfacing of personnel, equipment, and procedures used to track, command, and receive data from a spacecraft. This area is important for all space missions, and its importance is proportional to the degree of dependence of the mission on the successful performance of the mission operations system. Since this area is heavily dependent on effective human performance, an extensive program of simulated mission exercises is usually conducted by mission operations activities in order to detect and eliminate deficiencies in procedures as well as aspects of equipment design (or computer programs) which may lead to human error.

MOCKUP ACTIVITIES

Mockups and prototype equipment are important three-dimensional engineering tools used to determine the operational suitability of unmanned spacecraft and operational ground equipment. Whereas simulators and mission operations activities are implemented on the larger space programs, mockups are usually constructed for programs of average cost and complexity.

Several uses of mockups are:

(1) Reviewing and assuring the incorporation of adequate human engineering, serviceability, and safety criteria
(2) Checking out preliminary operational and maintenance procedures for clarity and accuracy of presentation
(3) Recommending revisions to the foregoing procedures if they permit task overloading or underloading or hazards involving man or equipment

PARTICIPATION IN PRERELEASE DESIGN REVIEWS

The prerelease design review is the project decision point preceding the transition to the fabrication of flight-type hardware. At this point, the detailed design is fixed and specifications are essentially complete. (See ref. 15.) At this time, the role of those responsible for the human factors area involves a review of the design package in order to assure that appropriate features have been provided to facilitate operation and servicing of the hardware. This review should make use of human engineering design criteria available from a number of sources (refs. 8, 9, 11, and 12); criteria and checklists for maintenance and serviceability features should also be used (see refs. 8 and 16 to 19 and tables IV and V in chapter 3 of the present publication). The results of this review of the design package should be reported in the design review meeting. The report should identify and make recommendations for correction of significantly undesirable or deficient human engineering or serviceability features.

FABRICATION AND FLIGHT HARDWARE TEST ACTIVITIES

The fabrication and flight hardware test stage of the project life cycle includes all activities following design and development testing but preceding activities at the launch site. It includes manufacture, assembly, inspection, in-process tests, qualification and flight acceptance testing (component level), subsystem and systems testing, and transportation of the system article to the launch facility. Throughout these activities, attention must be devoted to prevention of human errors and to correcting any that do occur. Although the prevention function on smaller programs is frequently not separated and formally identified as human engineering effort, careful consideration of various measures to prevent human error is an inherent part of the planning for all the activities in the fabrication and flight hardware test stage.[5] The correction function, on the other hand, is more centralized and on both large and small programs is usually approached through the discrepancy and trouble-reporting system(s) which the project uses.

HUMAN ERROR INVESTIGATION AND ANALYSIS

In order to correct and prevent recurrence of human errors and human-induced failures, it is necessary to study discrepancies which have occurred in production, assembly, handling, and test operations and to identify and characterize the specific human factors contributing to them. This may be accomplished by:

(1) An investigation of personnel process and workmanship errors which are critical or hazardous to system operation
(2) The reviewing of recurring workmanship errors which, though not critical as single events, may reflect basic deficiencies in design, procedures, or manufacturing conditions and thus contribute to mission degradation or failure potential
(3) An investigation of testing and test procedural errors (on all space programs)

Particular attention must be given to all errors of a critical nature and to those of less critical nature which pose potential problems by their frequent occurrence.

An essential prerequisite for accomplishing the foregoing activities is an effectively implemented discrepancy or trouble reporting system. (See also ref. 22, par. 14.3.) Reports in the system must be written on a current basis by manufacturing, test, engineering, or inspection personnel following the detection of an equipment or operational discrepancy. Although the reports are chiefly concerned with equipment failures and deviations from specified performance, they also identify such human errors as:

(1) Use of improper tools
(2) Inadequate handling
(3) Installation of wrong items
(4) Failure to make the proper connections
(5) Failure to follow instructions, drawings, or test procedures
(6) Failure to provide required items (such as tooling, test equipment, or protective equipment) for manufacturing, test operations, etc.

OBSERVATIONAL STUDIES

A second important step following detection and recording of human errors involves investigation to obtain additional information on basic causes or original sources. These kinds of data,

[5]References 20 and 21 describe some methods of preventing human errors in inspection activities.

rarely included on trouble reports, may be obtained either by (1) interviewing and obtaining information from supervisory, inspection, and operator personnel involved, or by (2) performing observational studies of specific fabrication, assembly, and test operations where human errors are suspected of being of a critical type or have been occurring with a significant frequency.

An example of human factor followup on failure reports involves a case in which a series of these reports showed repeated instances of damage to the same diode (CR-12) of a direct-current power supply but gave vague descriptions of failure cause. An investigation to determine the cause of these repeated failures disclosed that accessibility to the diode for subassembly checkout was limited. Immediately adjacent to diode CR-12 were two 16-gage wires terminated on one post, although the hole on the post was designed for only one 16-gage wire. This resulted in the wires being wrapped around the post during initial assembly, which further complicated accessibility to the diode. The reported failures all involved separation of the anode from the body portion of diode CR-12, which was caused by personnel pushing the diode aside to gain access during maintenance and checkout activities. After this discovery of true failure cause, correction by redesign to provide adequate accessibility in this OGE system was a relatively simple matter.

PRELAUNCH AND OPERATIONAL ACTIVITIES

The phase covering prelaunch and operational activities begins with preflight assembly and checkout at the launch facility and extends through completion of the mission. Major human engineering and serviceability functions in this project phase are concerned with assuring human performance by observing and reviewing both (1) flight test procedures of manned spacecraft and complex unmanned vehicles (including document review and observation of "dry" test runs), and (2) maintenance operations involving both spacecraft and operational ground equipment.

The activities described here are of particular importance to all programs. Although the use of human engineering specialists for them may be limited to programs of high national significance, these activities must be conducted diligently on other programs also, usually by test engineering or quality assurance personnel.

The following representative activities are applicable during critical flight test and maintenance operations:

(1) Observing the implementation of specific test, maintenance, and support procedures to determine which equipment features are unsafe or inconsistent with realistically expected human effort or capability
(2) Identifying deviations and difficulties in test or maintenance procedure documents which could lead to human error in task performance
(3) Reviewing accessibility and reliability features (especially during initial installation of test equipment and facilities) to assure that equipment can be inspected, adjusted, and repaired with minimum man-hours, experience, and support equipment
(4) Revising personnel work space arrangements and operating configurations for more effective performance
(5) Recommending changes in working environment where necessary in order to provide safe and reliable launch operations and facilities
(6) Reviewing all failure and trouble reports generated during these activities to assess and correct human error problems

As project activity progresses, frequent changes usually occur which make necessary a continual updating of test and operating procedures. Throughout this process, adequate attention should be given to eliminating potential sources of human error, particularly when the changes are part of the corrective action following reported failures or discrepancies.

PERSONNEL QUALIFICATIONS, TRAINING, AND MOTIVATION FOR ALL PHASES

Important human-factor areas, the detailed treatment of which is outside the scope of this publication, include selection, training, supervision, and motivation of personnel. Problems in these areas are damaging at any phase of project life but can become especially acute from the beginning of fabrication through mission completion. It should be borne in mind that much of what is gained by sound effort in all other phases of project activity can be negated by inadequate attention to these factors.

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CHAPTER 3

Specific Application to an Unmanned Satellite System (the Micrometeoroid Deep Space Satellite)

Chapter 2 has described a method for categorizing space projects by size and significance and then selecting human engineering activities (table II) to fit each category. It has also given a general description of each of the human engineering activities listed in table II. The present chapter describes the application of that general guidance to a specific project. The system chosen for the illustration is a hypothetical cislunar Micrometeoroid Deep Space Satellite (MDSS), a concept based on studies of an unmanned satellite program of medium-to-small cost and complexity.

The primary mission objective of the MDSS is to obtain information on micrometeoroid penetration rate variation with distance from the Earth. A long-life, high-reliability spacecraft having a number of state-of-the-art sensors with similar or overlapping sampling windows was recommended for accomplishing this goal. (See fig. 1 and ref. 23.) After extensive study, the Atlas-Agena D launch vehicle was also selected to place the spacecraft in a highly elliptical orbit for a period of 6 to 12 months. This MDSS and its associated operational ground equipment systems will provide the framework for describing a small project's program of activities for eliminating sources of human error. As a practical matter, the illustration here will not consider human engineering activities associated with launch vehicle development, since a spacecraft program of this type treats the launch vehicle as a "shelf item" except in its testing and operating interfaces with the spacecraft.

MDSS PREDESIGN AND EARLY DESIGN ACTIVITIES

In order to select appropriate activities for this program, first refer to table I and note that the spacecraft falls in category C and the operational ground equipment (OGE) falls in category H. (The interfacing of spacecraft and launch vehicle will be considered as an area of spacecraft development and test.) Next, in order to determine predesign and early design activities, refer to table II which recommends the following activities:

(1) Review system requirements and analyze mission; use an intermediate level of effort for spacecraft and full effort for OGE
(2) Allocate functions by man-machine analysis; use an intermediate level of effort for both spacecraft and OGE
(3) Prepare operator task analyses; use intermediate effort for the OGE only
(4) Human engineering of displays, controls, etc.; use intermediate effort for the OGE only
(5) Prepare serviceability and maintainability analyses; use full effort for both spacecraft and OGE
(6) Participate in system and subsystem design reviews and design trade-offs; use intermediate effort for both spacecraft and OGE

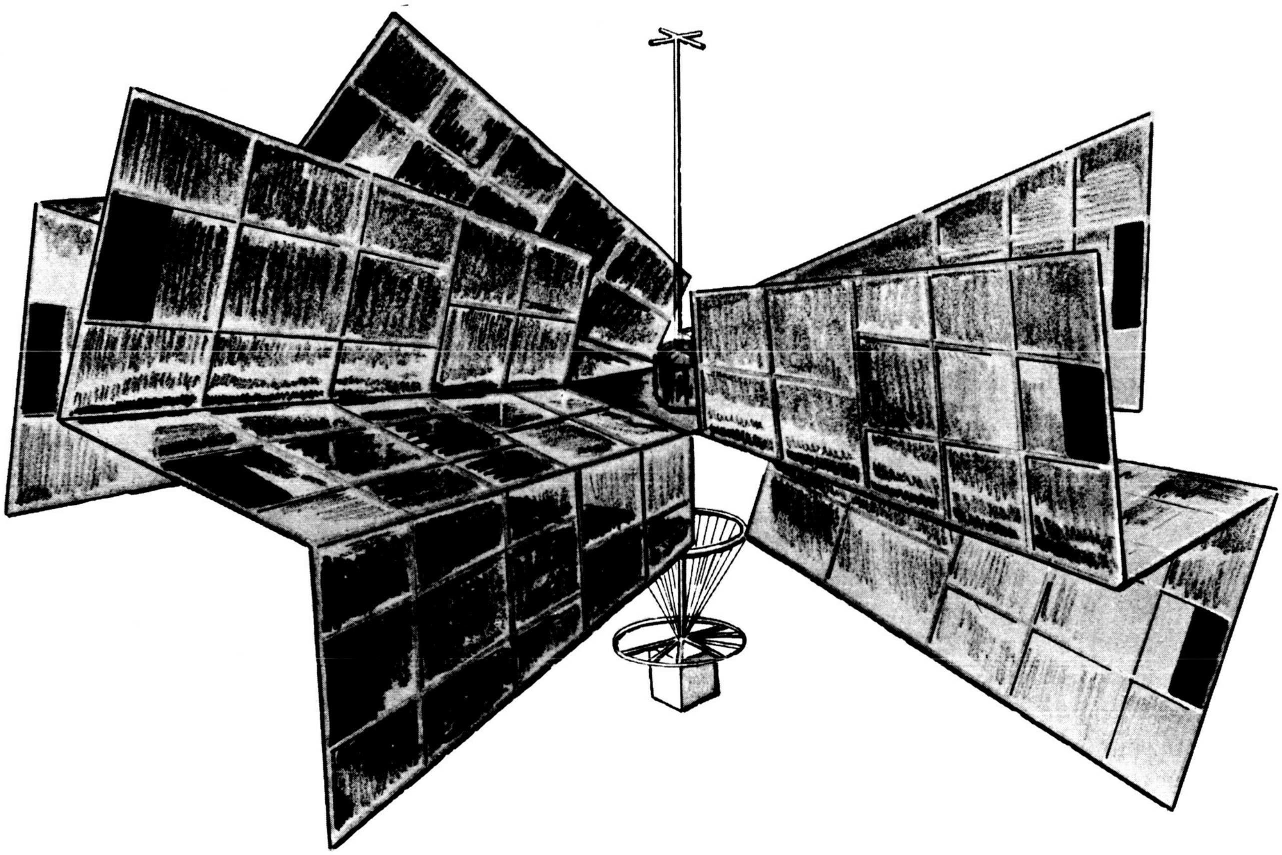

Figure 1.—Preliminary configuration concept for MDSS (ref. 23).

The implementation of these functions for this program is described in the following paragraphs.

REVIEW OF REQUIREMENTS AND PREPARATION OF FUNCTION ANALYSES

Review of Requirements

The first step in determining personnel activities on the MDSS is the identification of the functions of the system and its mission. This involves a review of requirements, followed by the preparation of function analyses and derivation of specific man-machine functions.

MDSS system requirements data are obtained from:

(1) Conceptual study reports
(2) Customer requests for proposals, the preproposals, and the actual proposals
(3) Documents describing unmanned satellite concepts similar to the MDSS
(4) Information received through project or customer personnel interviews or correspondence

From the foregoing sources, the following representative requirements are listed for both the spacecraft and its OGE. The MDSS spacecraft requirements are:

(1) Determine micrometeoroid penetration rate variation with distance from Earth

(2) Obtain and relay information on impact rate variation with distance from Earth

(3) Collect and communicate information on mass distribution in the same environment

(4) Determine and send data on velocity distribution in the same environment

The MDSS OGE requirements are:

(1) Provide for command control of the spacecraft, both hardline and RF, to exercise it through all operational modes

(2) Provide capability for calibration and checkout of each spacecraft subsystem to insure performance to specifications

(3) Provide external power source to the spacecraft simulating spacecraft power, and provide monitoring, switching, and charging of spacecraft supplies

(4) Provide electrical simulation of the micrometeoroid environment as a primary stimulus, and provide stimuli for other spacecraft sensors

(5) Provide for reception and decommutation of all telemetry data

(6) Provide mobility of checkout equipment to assure ease of transport between test areas

(7) Provide for mechanical handling and transportation of the spacecraft

Preparation of Function Analyses

The next step is the determination of the system functions[6] or capabilities needed to meet the foregoing listed requirements. Typical functions for the MDSS system include:

(1) Accumulating micrometeoroid penetration data through the use of counters

(2) Sensing and transmitting primary data by telemetry

(3) Using an impact simulator to check out spacecraft capacitance panels

(4) Using an established range and range rate tracking system to track the spacecraft

(5) Receiving and displaying all signal data including quick-look diagnostic and scientific measurements

(6) Using checkout equipment to pinpoint faults down to the replaceable component level

(7) Monitoring of specific spacecraft parameters, such as RF power output and spectrum of spacecraft transmitters

(8) Positioning operational ground equipment vans in accessible positions for launching the MDSS

(9) Recording and storing transmitted data by using a magnetic tape recorder as the prime recording medium

The above general MDSS functions, and others determined during system definition phases, provide the basic data for preparing function analyses, also known as man-machine analyses.

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[6]Reviewing mission requirements and specifically identifying system functions are essential steps in the basic planning of the whole design and development effort. They are shown here to illustrate their use in preparing man-machine analyses.

These analyses are generated on subsystems requiring man in their operation, test, or maintenance. According to table II, only intermediate effort is recommended in this area for the MDSS. That effort should be applied to the following systems:

(1) Onboard spacecraft electronic and electrical equipment
(2) Command control, instrumentation, telecommunications, data handling, and associated OGE equipment systems (all housed in a mobile van)

In order to perform man-machine analyses, a table is usually constructed which shows each function, the specific requirements which apply to it, and an allocation of which parts of the function are to be performed by man and which by machine. Exhibit 2 shows such a table applicable to the MDSS OGE function of data recording. It may be considered a typical example useful for analyzing other functions involving man in unmanned satellite activities.

The allocation of functions requires (1) an examination of the possible appropriate combinations of man-machine capabilities for achieving the system functions and then (2) selecting those combinations most likely to achieve maximum system effectiveness.

Selection of the best possible combination of man-machine capabilities for the MDSS is of necessity a series of approximations. The first approximations are made with reference to the various functions listed at the start of this section. For example, "the MDSS will be tracked using the NASA Range and Range Rate tracking system with an active transponder in the spacecraft." In this case, a final approximation of the best combination of capabilities will be made only after project management finally agrees on the most suitable mode for tracking the spacecraft.

The foregoing approximation approach was used in assigning the following MDSS functions to human operators:

(1) Interpretation of telemetered micrometeoroid penetration data (obtained from overall data collecting and processing activities)
(2) Decision making (as in maintenance activities)
(3) Handling unexpected occurrences (such as detecting deviations from required orbit and programming flight path corrections)
(4) Controlling and monitoring equipment performance (as in ground-station handling and monitoring of primary data transmission from the spacecraft)

Typically, this allocation of operator functions was governed by consideration of man-machine capabilities weighed in a trade-off with the factors of:

(1) Equipment availability
(2) Economy
(3) Simplicity of operation
(4) Reliability
(5) Mobility of ground equipment
(6) Maintainability

System function	Requirement	Function allocation	
		Machine	Man
Data recording	1. Spacecraft telemetry data will be received by one ground station. Orbit period is 6 days. Minimum daily visibility is 3 hours. Recorded data for 24 hrs must read out in 60 min maximum. 2. Onboard recording of micrometeoroid data must be continuous (minimum interruption for readout) and recording of spacecraft data must be at frequent intervals (3 min maximum, except during readout).	Ground recording must accommodate spacecraft readout. Spacecraft will have two-channel recorder. One will record commutated engineering data on status of spacecraft functions; the other will record continuous data on micrometeorite impacts. Both recorder channels will be readout through a single telemetry channel.	Personnel will determine from tracking and inquiry signals when to command readout. Readout and recording devices will be started at appropriate time. Initiate readout, select readout speed, switch back to "recording" mode.
	3. Record raw and processed telemetry data on ground.	Record incoming raw data as received on electromagnetic tape.	Turn recorders on and off. Insert blank reels of tape. Remove and store filled reels of tape.
	4. Record with minimum reliance on man during critical periods.	Use two main recorders. Initiate No. 1 manually 5 min before start of readout. Initiate No. 2 automatically 7 min before No. 1 exhausts tape.	Set up and check condition of recorders prior to each readout period. Start recorders at appropriate time prior to data reception.
	5. Provide maximum practicable assurance in ground recording system against loss of raw telemetered data.	See above. Recorders No. 1 and 2 automatically overlap. Have recorder No. 3 on standby.	Monitor recorder operation during readin. Switch to standby recorder if main recorders are detected to operate incorrectly.
	6. Provide visual record in real time during readout of 10 most vital engineering function parameters to permit assessment and compensation for possible spacecraft malfunction.	Decommutate 10 vital spacecraft parameters and display on strip chart recorder or other device in real readout time.	Monitor vital parameters and give appropriate commands to spacecraft in event of spacecraft malfunction. After satisfactory readout, initiate command to switch spacecraft back to "recording" mode.
	7. Make permanent visual record of all telemetered parameters. Each parameter must be recorded separately on a calibrated time base.	Use onboard clock to feed five-min interval signals onto onboard data tapes. Feed data on orbital coordinates, date, and Z time onto raw data tape at ground telemetry station. Decommutate engineering data and make separate printouts of engineering parameters. Automatically add position and time data to each printout.	Use and store visual records. Store raw data tapes.

Exhibit 2.—Typical man-machine function analysis format.

These factors are important not only in generating initial MDSS function analyses and allocations but also in updating these materials during the latter phases of system development.

PREPARATION OF OPERATOR TASK ANALYSES

When the development of man-machine function analyses is accomplished, attention is directed to deriving personnel tasks from them. Reference to table II indicates task analyses should be prepared at an intermediate level of effort, and only for those MDSS systems (OGE systems in this case) specifically involving human performance requirements and behavior.

The task analysis effort results in a description of the activity of a man while he interacts with a major equipment unit in performing activities. Human behaviors are identified and described, with further detail added as more data on OGE equipment and personnel are obtained throughout the design phase. An example[7] of a task analysis for a programmed MDSS operational ground equipment activity is presented as exhibit 3. (See refs. 24 and 25 for more comprehensive descriptions of task analysis techniques.)

HUMAN ENGINEERING OF DISPLAYS, CONTROLS, AND OTHER EQUIPMENT FEATURES

Information from the foregoing task analyses is especially of value in the human engineering of the operational ground equipment to be operated by MDSS personnel. The OGE for the MDSS is of the checkout type, mounted in standard racks and located in a transportable van. Racks can be classified according to their functional usage as:

(1) Command control rack
(2) Power control and monitor rack
(3) Signal handling rack
(4) PCM decommutation rack
(5) Tape recorder rack
(6) Strip chart recorder rack

Human factors inputs for these major components are concerned with displays, controls, panels, chassis, and other associated equipment in basic operational configurations. These inputs are derived from human engineering principles and design criteria, which are supported primarily by empirical studies and logical, long-standing usage. (Ref. 11 presents a complete description and evaluation of design criteria for a number of human engineering areas.)

PREPARATION OF SERVICEABILITY AND MAINTAINABILITY ANALYSES

Following the guidance of table II, note that the serviceability and maintainability analysis area requires full effort in application of human engineering considerations to the MDSS project. These analyses apply to both the spacecraft and the OGE. The objective is to review the design to detect features which might make maintenance and service operations difficult or which provide unnecessary opportunities for misuse or equipment damage. It is desirable to conduct this review in conjunction with other human engineering design efforts (such as that described in the preceding section for the MDSS OGE) if the hardware in question calls for it.

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[7]This format is directly applicable for analyzing tasks on equipment similar to the MDSS OGE.

FUNCTION 1.0 SIMULATION OF MICROMETEOROID PENETRATION ON S/C

By____ Date ______ FUNCTIONAL ACTIVITY 1.1 PREPARATION FOR IMPACT SIMULATION Page 1 of _

TIME	TASK	EQUIPMENT (DISPLAYS/CONTROLS)	DISPLAY INDIC.	OPERATOR ACTION	OPERATOR DECISION	EQUIPMENT RESPONSE	REMARKS
(Estimated time to perform a task in hrs,min.)	(Group of related activities required to perform a functional activity)	(Identification of equipment involved in performing a task)	(Description of display inputs associated with task)	(Description of operator action required to perform task)	(Description of operator decision-making behavior)	(Description of motor outputs and/or equip. feedback)	(Potential malfunctions, consequences, & corrective action are included here)
Pre-Countdown (T- __ ')	1.1.1 Turn on simulator test set power	Power control and monitor panel with switch/indicator	Impact Simulator "POWER ON" light off	Depresses "POWER ON" switch/indicator	Assures simulator power is on	"POWER ON" light illuminates	
	1.1.2 Check Impact Simulator panel indicators	Impact Simulator panel indicators and switches	Expected values displayed	Depresses appropriate switches & observes values	Decides Impact Simulator ready for test	Appropriate values and parameters are shown	Wrong value may be included in test data if operator fails to scan entire panel.
	1.1.3 Verify mounting of capacitor panels	MOPS voice communication equip. from van to launch site	-	Verbally confirms mounting of capacitor panels	Assures capacitor panels properly mounted on spacecraft	Capacitor panels mounted	-
	1.1.4 Perform check of in-line test connector circuitry	Impact Simulator panel with switch/indicators	Lights indicate normal or malfunction	Depresses appropriate switch/indicators	Initiates corrective action if lights indicate malfunction	Lights indicate normal condition	All capac. panels ready to receive momentary shorts from simulator

Exhibit 3.—Preliminary task analysis of an MDSS OGE activity.

Serviceability and maintainability analyses are best implemented with the aid of qualitative checklists and formats. These are available from a number of sources such as references 17 and 26 for the OGE and references 18 and 19 for any type of equipment.

Table IV presents a checklist of serviceability criteria for the MDSS spacecraft, specifically the modules housing critical electrical and/or electronic equipment. These criteria provide for adequate accessibility and for other design features which will substantially reduce chances for human error in operations. Additional checklists for racks and chassis comprising the larger portion of the MDSS OGE may be found in table V. Tables IV and V should be used in early design, first by the equipment design engineers and later by those engineers responsible for reviewing the design to assure that it is adequately serviceable.

PARTICIPATION IN PRELIMINARY DESIGN REVIEWS

The human engineering effort described in the two immediately preceding sections constitute the majority of human factors activities required during the MDSS design phase. The one important effort remaining involves participation in preliminary system and subsystem design reviews planned for unmanned satellite programs of the MDSS type. The purpose of applying attention to human engineering areas in these reviews is to assure that initial concepts and design requirements are reevaluated against current state-of-the-art information and updated mission requirements.

Human factors engineering at the preliminary design review is focused on determining if previously identified manned activities will adequately and reliably satisfy system and subsystem requirements. Special attention should be directed to the man-machine functions allocated for MDSS system operations. (See section entitled "Preparation of Function Analyses.") Questions to be considered in reviewing input documentation or, if necessary, to be asked in the review meeting are:

(1) Have any initial MDSS system or subsystem requirements been neglected in assessing and recording human capabilities for satisfying them?
(2) Have any recent or revised requirements been overlooked in the MDSS analyses previously conducted?
(3) Does the proposed MDSS design configuration and function allocation take full advantage of combined man-machine capabilities (as in determining which functions will be manual, which automated, and which semiautomated)?
(4) Have functions been assigned to MDSS equipment which lead to deficient operation, and can humans perform the same functions more effectively (or is the reverse true)?
(5) Are MDSS function analysis reports satisfactory as basic data for follow-on human engineering efforts?
(6) Does the design incorporate preventive features, which respond to human factors trouble experience from similar equipment?

Recommendations and results from preliminary MDSS design reviews will serve as important input material for succeeding (prerelease) design reviews.

MDSS DEVELOPMENT AND PROTOTYPE TEST ACTIVITIES

In the development and test activities, the human engineering efforts applicable to the MDSS system, as determined from table II, are:

(1) Monitor the incorporation of human engineering and serviceability criteria in design of spacecraft and OGE—intermediate effort
(2) Prepare personnel requirements data for OGE—intermediate effort
(3) Assist in the development of operational and maintenance procedures for spacecraft and OGE—full effort

Table IV.—Serviceability and Maintainability Criteria for Modules in MDSS Spacecraft

A. Accessibility

1. Modules quickly and easily removed and replaced without damaging other adjacent components
2. Module replacement on individual basis (not requiring removal or disconnection of other modules)
3. Module parts requiring most frequent access in the most accessible locations

B. Handling considerations

1. Mounted so that parts can be easily inspected, checked, replaced
2. Units provided with grips for one-man carrying (if weight is 10 to 45 lb)
3. Grips at least 4-1/2 in. wide by 2 in. deep
4. Lifting eyes (suitably labeled) on units weighing in excess of 90 lb
5. Provide modules with rests for servicing where feasible
6. Provide for easy removal of irregular or fragile extensions (such as wave guides, cables, and hoses) to facilitate handling
7. Where feasible, cabling long enough to permit checkout of module while part of system
8. Replacement cables with easily accessible connector at each end are desirable
9. Provide adjacent units with different types of connectors to prevent misconnection

C. Ease of adjustment and repair

1. No tool requirements other than for required adjustments or where remove-and-replace fasteners require commonly available tools
2. Control adjustments should be located on module face with positive covers to prevent accidental disturbing
3. Displays should indicate malfunctions to level of remove-and-replace components
4. Modular connectors reliable and capable of quick disconnect
5. Minimum of fasteners required for installation
6. Modules sufficiently uniform for direct interchangeability without adjustment

D. Ease of identification

1. Modules labeled and coded to indicate correct unit for replacement
2. Highly similar units keyed to prevent insertion of wrong units

Table V.—Serviceability and Maintainability Criteria for Racks and Chassis in MDSS OGE

A. Handling considerations

1. Mounted on slide and/or revolving hardware so that parts can be easily inspected, checked, and replaced
2. Chassis provided with grips for one-man carrying (if weight is 10 to 45 lb)
3. Chassis provided with grips for two-man carrying (if weight is 46 to 90 lb)
4. Grips at least 4-1/2 in. wide and 2 in. deep
5. Lifting eyes (suitably labeled) on equipment weighing in excess of 90 lb
6. Rests or stands should be part of chassis or rack where feasible
7. Provide for easy removal of irregular or fragile extensions (such as wave guides, cables, and hoses) to facilitate handling
8. Provide cabling long enough to permit checkout of chassis while part of system
9. Provide replaceable cables with easily accessible connector at each end
10. Provide adjacent items with different types of connectors to prevent misconnection
11. Cabling out of the way and not likely to be pinched by doors, lids, etc., walked-on, used for hand-holds, or bent around sharp corners
12. Cabling removable and replaceable without removing other parts

B. Ease of identification

1. Chassis permanently and clearly labeled with information required to relate it to system
2. Test points provided on chassis exterior
3. Lubrication points labeled and accessible
4. Test points labeled with signal values, wave shapes, etc. (when space is available)
5. Primary test points located and coded so as to be readily distinguishable from secondary test points

C. Ease of adjustment and repair

1. Removable assemblies and units generally replaceable with common hand tools and removable without damaging adjacent units
2. Need for special tools minimized; required special tools secured to equipment near point of use
3. Schematics and instructions attached to or adjacent to chassis
4. Mechanical guides provided for screwdriver adjustments without the aid of vision

Table V.—Serviceability and Maintainability Criteria for Racks and Chassis in MDSS OGE (Continued)

C. Ease of adjustment and repair (continued)

5. Chassis parts arranged in family groups with outlining of groups by painted borders, etc.
6. Self-checking features (built-in meters, warning indicators) provided
7. Sensitive adjustment points appropriately located and guarded
8. Test-point panels provided and labeled with clear instructions
9. Primary test points grouped in a line or matrix reflecting sequence of tests to be made
10. Calibration instructions logically integrated with calibration controls
11. Transmission line terminals marked with appropriate line impedance
12. Lamps replaceable from the front
13. Chassis capable of being locked in both open and closed positions
14. No termination of test cables on control and display front panels

D. General considerations (including safety)

1. Drawers and racks designed so that they operate with a force of less than 40 lb
2. Guards and shields provided to prevent damage to delicate or sensitive parts during movement
3. Limit stops, guards, and/or retaining devices provided as part of basic chassis (but stops may be overridden for assembly removal)
4. Guide pins or their equivalent incorporated on units to assist in alinement during mounting, especially on modules that contain or function as connectors
5. Racks and drawers arranged so that minimal place-to-place movement occurs during checkout
6. All external metal parts at ground potential
7. No hot leads exposed by disconnected connectors and plugs
8. Interlocks and warning indicators provided where potentials exceed 70 volts
9. Contacts, terminals, etc. with potentials more than 70 volts rms provided with guards or barriers; voltage level prominently displayed
10. Operation of switches or controls initiating hazardous operations based on prior operation of a related or locking control
11. Conspicuous placards mounted adjacent to high voltage equipment, equipment extremely hot, etc.
12. Avoidance of "tapped through" holes which allow use of wrong length screws
13. Care exercised in fusing, soldering, and flux removal operations to prevent damage to (or unsoldering of) adjacent parts or areas
14. Edges and corners rounded or finished to prevent injury

(4) Participate in mockup activities for spacecraft and OGE—intermediate effort
(5) Participate in prerelease design reviews for spacecraft and OGE—intermediate effort

MONITORING THE INCORPORATION OF CRITERIA

During MDSS design, human engineering efforts were concerned with determining preliminary human performance requirements and with providing serviceability inputs to equipment design. Now, as the MDSS goes into development and testing, a two-fold followup activity is conducted. (In the MDSS case, the effort should be performed at a relatively low manning level by project personnel who are assigned human engineering responsibility but who are usually not specialists in the area.) The two-fold activity is as follows: (1) The design and the prototype hardware are reviewed to assure that earlier recommended design features are incorporated; and (2) these earlier recommendations, and the analyses underlying them, are revised as appropriate to keep pace with refinements in design and with added data received through testing.

DEVELOPMENT OF OPERATIONAL AND MAINTENANCE PROCEDURES

Throughout the development test phase, the human engineering activity should place heavy emphasis on assisting project personnel responsible for developing the procedures for testing, checking-out, and maintaining the MDSS. The primary effort will be devoted to reviewing these procedures to assure that they are as complete and as "error-minimal" as possible.

Procedure Characteristics

Throughout procedure development, preliminary drafts of MDSS instructional and procedural documents are reviewed for such characteristics as:

(1) Clarity and conciseness in describing test and maintenance activities step-by-step (statements having potential ambiguity should be deleted or revised)
(2) Appropriate use of abbreviations and caution statements (see table VI)
(3) Indications of the time for performing a specific operation
(4) Completeness, in including all information necessary to do the job (e.g., what readings should be obtained, what are the tolerance limits, and what should be done if out-of-tolerance conditions arise)
(5) Use of illustrative material (tables, figures, charts, etc.) only <u>where necessary</u> to clarify and complement procedural steps

Table VI.—Items for Evaluating Caution and Abbreviation Usage in MDSS Procedures (ref. 27)

Caution usage	Abbreviation usage
Used sparingly as is consistent with real need Used for operating procedures, practices, etc. which, if not strictly observed, will result in damage to, or destruction of, equipment Generally precede the applicable text	Used when space may be saved Held to a practicable minimum consistent with clear presentation Defined, if uncommon, in the introduction of each document Not used where there is any doubt as to what is abbreviated Only the most commonly used terms are abbreviated, e.g., units of measurement and compass direction

(6) Inclusion of provisions for meeting contingencies or problems outside of normal job operations (what to do if a required reading is not obtained, how to respond to unexpected power loss, etc.)
(7) Consistency of procedures used in preflight activities with those to be followed in operational use

An illustration of a test procedure possessing the above preferred items is given as example B of exhibit 4. This exhibit contrasts two sets of procedures, A and B. Both were written as instructions for making the same connections to launch vehicle engine components prior to a pressure switch checkout. The differences between the "bad" procedure (example A) and the "good" procedure (example B) for doing the same tasks are evident when they are reviewed for clarity, completeness, accuracy, and other worthwhile features.

Another example of an inadequate operating procedure for checking a propellant system's flow rates and pressures is shown as exhibit 5. Although the procedure appears to be complete and explicit in stating what pressure and flow rate readings and recordings are to be made, it has the following flaws which are likely to cause human error:

(1) It calls for the recording of three different readings of chamber pressure in step c. The "transducer readout" value is specifically indicated in psia. However, step b requires the operator to set the chamber pressure to a stated value expressed in psig, but labeled "transducer reading." It further complicates the picture by adding a note which advises that the transducer reads absolute pressure. If it is assumed that the note is correct, step b should call for setting chamber pressure to 182±5 psia as read out directly from the transducer and not 170±5 psig.
(2) In step b the operator is instructed to set the chamber pressure within specified limits (170±5 psig) by operating the back-pressure valve. However, the operator is not told what he should do if he is unable to control the pressure within the limits by means of the back-pressure valve (possible alternatives may be to call the supervisor, shut down the system, perform certain diagnostic actions, etc.).

Updating of Procedures

It will be necessary to stay abreast of frequent changes to MDSS development test requirements by continually updating the system's test and operating procedures. Particular attention should be paid to incorporating corrective actions and revisions to test procedures promptly after the detection and reporting of discrepancies (especially those caused by human error). Corrections to procedures may be included, for example, in the form of an added or modified job step or as a caution or warning notice inserted in the text. These corrections should be made available to operating personnel promptly and such personnel should be required to familiarize themselves with the revised procedures prior to the start of the test concerned (and preferably on a daily basis).

PARTICIPATION IN MOCKUP ACTIVITIES

In the development phase, an intermediate level of human engineering effort would be devoted to mockup activities for the MDSS. This effort would primarily consist of inspecting the available spacecraft mockup[8] for possible human factors problems. Such equipment would especially

[8]A system of this type would usually build spacecraft mockups primarily for such purposes as determining fit of subassemblies, center of gravity, and cabling runs.

Example A—faulty set [a]	Example B—preferred set	
Step T. P. No. 739-2	Step T. P. No. 739-2	QC
7.0 EFFECTING OF TEST SET AND ADAPTER BOX CONNECTIONS	7.0 TEST SET AND ADAPTER BOX CONNECTIONS Task Started_____ Time_____ Date_____	
7.1 Insure that all switches on test set and adapter box, and also all valve regulators on the aforementioned equipment are in an off or closed position	7.1 Insure all switches on test set and adapter box are in OFF or CLOSED position 7.2 Insure all valves and regulators on test set and adapter box are in OFF or CLOSED position	
7.2 Insure that power cable is disconnected prior to disconnecting and/or connecting conn's to AGE or hdware.	7.3 Insure that facility power cable is disconnected from AGE prior to disconnecting and/or connecting electrical connectors to AGE or engine hardware 7.4 Insure vehicle IPS and APS power supplies are OFF during disconnection and connection of launch vehicle connectors at engine interface	
7.3 Connect 285516 Cable from 28660-14 A. B. in the following way: Connect the 66P8 Conn. to T. S. 66J8 Recep. and then connect the P2 Conn. to A. B. J4 Recep. before connecting the 270419 cable	7.5 Connect 285516 Cable (obtained from 285350-16 Adapter Box Interconnecting Kit) from 28660-14 adapter box as follows: 7.5.1 Connect 66P8 connector to test set 66J8 Receptacle 7.5.2 Connect P2 Connector to adapter box J4 Receptacle	
7.4 Connect 270418 cable as follows: Connect the P5 Conn. to A. B. J6 Recep. and then remove l. v. conn's from interface EL 1400 J7 and EL 1400 J8 Recep's; connect P11 and P12 to engine interfaces EL1400 J11 and J12, respectively.	7.6 Connect 270418 Cable as follows: 7.6.1 Connect P5 Connector to adapter box J5 Receptacle CAUTION Do not connect any cable connectors to engine interfaces until all launch vehicle connectors have been removed from engine interfaces. 7.6.2 Remove launch vehicle connectors from engine interface EL1400J7 and EL1400J8 Receptacles 7.6.3 Install protective closures or connectors 7.6.4 Connect P11 Connector to engine interface EL1400J11 Receptacle 7.6.5 Connect P12 Connector to engine interface EL1400J12 Receptacle	
Time (approx.) for entire operation_______	Task Completed_____ Time_____ Date_____	

[a] Omits important step after 7.2 in assuring vehicle power supplies are off.
No caution note or quality control (QC) check included in this example.

Exhibit 4.—Comparison of test procedures for performing same operations to connect test equipment to a launch vehicle.

FLOW TEST PROCEDURE - STEADY STATE

____ a. Set TV driver at 0 ma.

____ b. Actuate SOV. With solvents flowing, confirm that TV inlet pressures meet specified requirements. Set back pressure valve to produce a chamber pressure of 170 ±5 psig (transducer reading.)

NOTE

The Pch transducer is calibrated to read absolute pressure; hence, indicated pressure will be 170 psig plus barometric pressure (approx. 12 psi) or 182 psia. DVM reading is 1.82V.

____ c. Read and record the following steady state data: 0 ma

Oxidizer flowrate	____ cps (___ lb/sec)
Fuel flowrate	____ cps (___ lb/sec)
Ox TV inlet pressure	____ cps (___ lb/sec)
Ox TV inlet pressure	____ psig
Fuel TV inlet pressure	____ psig
Chamber pressure:	
Transducer readout	____ psia
Barom. press.	____ psi
Gage press.	____ psig
Back pressure gage reading	____ psig

____ d. De-activate SOV. Proceed to next data point.

Exhibit 5.—Example of faulty flow test procedure. Step b is confusing because the transducer reading appears directly as psia, not psig; also, step b does not tell the operator what to do if he cannot adjust chamber pressure to the specified limits by means of the valve.

be evaluated for the inclusion of desirable design criteria preventing human error in assembly, test, and serviceability functions. (See table V.) Human engineering design changes resulting from these mockup inspections would be incorporated during continuing development testing.

PARTICIPATION IN PRERELEASE DESIGN REVIEWS

Prerelease design reviews occur just prior to the release of engineering drawings for manufacturing. For the MDSS, table II recommends an intermediate level of human engineering participation in these reviews to uncover problem areas.

Project personnel responsible for reviewing MDSS designs should especially pay attention to those features related to the ease with which equipment can be operated and serviced. Information obtained from preliminary design reviews should be used in checking for the incorporation of such items as:

(1) Adequate and safe arrangement and accessibility
(2) Coding and labeling (including schematics)
(3) Adequate cable and line routing
(4) Provision of test points
(5) Appropriate fasteners and connectors
(6) Ease of assembly, adjustment, and calibration
(7) Ease of handling (packaging, weight considerations, etc.)
(8) General safety provisions (for prevention of personnel hazards and/or equipment damage)
(9) Avoidance of blind-mating of connectors or tubing

Tables IV and V should also be used as backup checklists during prerelease reviews to detect potential maintenance problems and sources of human-induced failures. (Refs. 16 to 19 and 28 provide added serviceability and maintainability data and guidelines for those working on systems similar to the MDSS.)

For MDSS OGE specifically, the design review should also cover examination to detect potential causes of human error in <u>operating</u> the equipment. This should result in eliminating features[9] that:

(1) Violate "populational stereotypes," or the usual way of doing things (e.g., flipping a toggle switch "down" to turn <u>on</u> an MDSS recorder)
(2) Impose performance requirements in excess of user capability (e.g., too many displays to be monitored on the PCM decommutation rack at one time, or one display which combines too many kinds of information)
(3) Provide inadequate information or facilities for the user (e.g., displays hard to read, or coded in the wrong format; schematics for adjustment and calibration <u>not</u> attached to certain OGE electronic equipment)
(4) Contribute to unnecessarily difficult, fatiguing, or hazardous conditions (e.g., inadequate illumination and intolerable noise levels during mobile van test operations, or location of internal controls too closely to dangerous voltages)

MDSS FABRICATION THROUGH OPERATIONAL USE

A final reference to table II indicates that for the MDSS and similar unmanned satellites, human engineering activity during fabrication, test, prelaunch, and operational phases would include reviewing and analyzing failure reports for human errors during production and testing

[9]Based on pp. 64-67 of ref. 29.

operations, reviewing procedures, and observing specific maintenance and checkout activities at the launch sites. For the most part these activities would be performed at an intermediate level of effort.

It is emphasized that the meticulous review and "rehearsal" of all flight test and operational procedures is of paramount importance for any space system. Detection and elimination of potential sources of human error are an integral part of this activity. However, on a system of the MDSS type, this would be conducted as a mainstream project activity and often would not be identified as a separate human engineering activity.

APPENDIX A

Reliability Program Provision Concerning Prevention of Human Error

The following reliability program provision for space system contractors is taken directly from NASA Reliability Publication NPC 250-1 (ref. 5):

3.5 Maintainability and Elimination of Human-Induced Failure
The contractor shall give careful consideration to the maintainability of the system and to the elimination of potential sources of human-induced failure throughout the entire contractual effort—from basic design through operational use. This shall include the following:

a. A study of requirements for test, checkout, inspection, parts or components replacement, disassembly and assembly, and self-monitoring, followed by provision of access and other design features to facilitate performance of all checkout, repair and maintenance tasks.

b. An intensive effort directed toward making proper and safe use of the equipment convenient and toward making improper or unsafe use inconvenient or extremely difficult, thus enhancing the system's capability to be fabricated, handled, maintained and operated with maximum facility and minimum hazard to life and equipment. This effort shall cover the design of the equipment and all instructional material and training associated with its handling, storage, transportation, checkout and use.

Effective effort in these areas is an important means of enhancing reliability in any system, is particularly so in ground support equipment, and is absolutely vital in providing the necessary reliability for crew safety in manned spaceflight vehicles. Features to eliminate potential human-induced failures and to enhance maintainability of the system shall be given careful consideration in all design reviews.

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APPENDIX B

Definitions

The following definitions apply to terms as used in this publication.

Accessibility - A quality of design that permits ready and adequate access for testing, fault detection, and repair or replacement (ref. 30).

Checklist - A list of procedures or items summarizing the activities required in the performance of a task. A condensed guide. An on-the-job supplement to more detailed job instructions.

Cislunar - Of or pertaining to space between the Earth and the orbit of the Moon, or to a sphere of space centered on the Earth with a radius equal to the distance between the Earth and the Moon (ref. 30).

Component - A combination of parts, subassemblies, or assemblies, usually self-contained, which performs a distinctive function in the operation of the overall equipment (ref. 5).

Fail-safe design - Design considerations to prevent probable equipment failures or malfunctions which may injure the operator or the equipment (ref. 30).

Flow chart - Graphic description of the mission(s) which the space system is expected to perform and the things which must be done to the system before and after a mission (ref. 25).

Function analysis - A technique for identifying the human and/or equipment capabilities for adequately meeting system requirements. Man-machine function analyses (or allocations) are primarily conducted to determine whether functions will be performed by man, by machine, or by a combination of both.

Human engineering - The application of scientific knowledge concerning human limitations and performance capabilities to the establishment of requirements for accomplishment of the mission. The purpose is to minimize demands upon human skill, training, and manpower resources, and to maximize the effectiveness of man-equipment combinations (ref. 30).

Human factors - Used in a broad sense to cover all biomedical and psychosocial considerations pertaining to man in the system. It includes principles and applications in the areas of human engineering, personnel selection, training, life support requirements, job performance aids, and human performance evaluation (ref. 30).

Human-induced failures - Those failures and malfunctions of equipment components directly attributable to some act or omission by a human operator. Examples of human-induced failure events include: Activation of the wrong control, rough handling, and incorrect wiring. Sources of human-induced failures may include: Poor design, incorrect process or test procedures, improper inspection, and inadequate training or supervision.

Human operator - A person who participates in some aspect of operation or support of a space system and its associated equipment and facilities.

Human-performance assurance - A method or approach for reducing and eliminating sources of human-induced failures by implementing an adequate human engineering and serviceability effort during the project life cycle of space systems.

Launch vehicle - The part of the space vehicle which furnishes the propulsion and guidance during the initial part of the trajectory to provide the prescribed velocity, position, and attitude required for injection into the desired trajectory.

Launch window - The mission conditions which impose launch time limitations on the launch vehicle for any given trajectory, such as relative position of Earth and Moon or planets, midcourse propulsion capabilities, guidance limits, etc. (ref. 30).

Link analysis - An analysis of the visual, auditory, and tactual links between man and machine or between one man and another involved in an operation. Primary objectives are determination of the importance of links, frequency of their use, and their adequacy.

Maintainability - That quality of the combined features of equipment design and installation which facilitates the accomplishment of inspection, test, checkout, servicing, repair, and overhaul with a minimum of time, skill, and resources in the planned maintenance environments (ref. 5). Maintainability includes both "serviceability" and "repairability." This manual emphasizes the former term in its discussions of maintainability, since serviceability is essentially an equipment design characteristic important in assuring reliable and effective system performance.

Maintenance - The function of retaining material in or restoring it to a serviceable condition (ref. 30).

Maintenance task - Any action(s) required to preclude the occurrence of a malfunction or restore an equipment to satisfactory operating condition (ref. 30).

Man-machine function analysis - See "Function analysis."

Man-rated space vehicle - Space vehicles for manned flight which have achieved the standards of performance and reliability previously established as reasonably acceptable for its class of equipment (ref. 30).

MDSS - Micrometeoroid Deep Space Satellite (ref. 23).

Micrometeoroid - Meteoroids less than 1/250th of an inch in diameter.

Mission analysis - A comprehensive evaluation of all the parameters which affect the events of a mission (ref. 30).

Mission profile - A time-sequence description of the events required, as well as the necessary locations and conditions of their occurrence, in order to accomplish the objectives of the mission.

Mission task - The specified purpose for which a device must perform (ref. 30).

Mockup - A replica or dummy. For human factors analysis a mockup is usually full-sized.

Mockup inspection - An inspection of a mockup to determine the operational suitability of the configuration and general arrangement of the operational equipment represented (ref. 30).

Module - A combination of components, contained in one package or common to one mounting, which provides a complete function to subsystems and systems in which they operate (ref. 30).

Operational ground equipment (OGE) - A functional part of a system which operates with the aerospace vehicle or end item as an essential operating element thereof (ref. 30).

Operational use - The period from beginning of launch countdown through mission completion.

Operator task - A group of related activities required in performing (with other tasks) a more comprehensive system functional activity.

Personnel requirements - Human activities and behaviors (individual and crew) required for the adequate performance of operator and maintenance tasks.

Procedure - A particular course or mode of action for conducting a business or the formal instructions carrying management approval and governing and prescribing the means by which personnel are to operate to accomplish an objective (ref. 30).

Program - A related series of undertakings designed to accomplish a broad scientific or technical goal. Attainment of such long-range goals may be accomplished by implementation of specific projects (ref. 30).

Project - A scheduled undertaking, within a program, which may involve the research and development, design, construction, and operation of system and associated hardware, or hardware only, to accomplish a scientific or technical objective (ref. 30).

Prototype - An original or model from which the final hardware design evolves (usually through a process of refinement).

Quality control - A management function to control the quality of articles to conform to quality standards (ref. 22).

Reliability - The probability that system, subsystem, component, or part will perform its intended functions under defined conditions at a designated time and for a specified operating period (ref. 5).

Repairability - The probability that, when the actual repair begins, the system will be repaired in a given period of time with a given manpower expenditure (ref. 30).

Serviceability - Equipment design, configuration, installation, and operation that minimize maintenance, inspection, and servicing (ref. 30). Serviceability analyses are performed to determine what must be accomplished to achieve this objective. (See also "Maintainability.")

Simulation - A set of test conditions designed to duplicate field operating and usage environments (ref. 30).

Time-line analysis - Reducing or charting a function on a time base. The analysis can be performed first at the broader functional levels and then be repeated with successively greater precision at successively narrower levels of function.

Work space layout - A design of a work area to include provisions for seating, physical movement of human operators, operational maintenance, and other factors permitting adequate person-to-person contact and man-machine interaction (ref. 25).

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